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Review of technological advances for the study of fish behaviour in relation to demersal fishing trawls

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In demersal trawling, there is a need to develop more species-selective trawls to minimize discarding in multispecies fisheries. This requires observational tools that can operate at depths and light levels encountered by the commercial fleets. There is a growing tendency towards more fishery-independent stock-assessment methods using survey trawls to provide population indices. This requires the ability to quantify the herding and capture efficiency by species and age groups of such gears. A range of optical and acoustic observation techniques has been developed over the past few decades to assist in these goals. In this paper we update the review of technologies presented at the ICES Symposium on Fish Behaviour in Relation to Fishing Operations held in 1992. Since then, considerable advances in optical, acoustic, and data-processing technology have been made.

Keywords: behaviour, fishery acoustics, selectivity, survey trawls, trawl instrumentation.

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Introduction

The evolution of trawl design has largely been a direct consequence of the fishermen's understanding of fish behaviour. However, the study of this subject has become increasingly important for fishing gear technologists wishing to develop more species-selective trawls to minimize discarding and by-catch. Recent shifts toward fishery-independent stock-assessment methods have resulted in a desire to obtain absolute estimates of abundance from surveys. This requires information on species-specific herding and catching efficiency of the survey trawls used.

Urquhart and Stewart (1993) provide an excellent review of techniques available for observation of fish behaviour, including the use of SCUBA, manned and unmanned submersibles, developments in low light underwater cameras, and acoustics. The wealth of knowledge gained using these technologies has greatly assisted the development of measures for reducing some of the negative impacts associated with trawling, such as by-catch of unwanted species and discarding. Escape panels (e.g. Broadhurst, 2000; Graham *et al.*, 2003), grids (Larsen and Isaksen, 1993), and separator trawls (Main and Sangster, 1985) are a few examples of devices now routinely used in many fisheries worldwide.

Despite this progress, there is a necessity to obtain behavioural observations from greater depths, at lower light levels, and in conditions where a new generation of tools is required. Additionally, many of the previous observations were qualitative by nature, whereas quantitative data are now needed, for example, to estimate survey trawl efficiency. Since Urquhart and Stewart (1993), there have been developments in optical and acoustic instrumentation and also in post-processing techniques. In this paper we aim to update and review the most recent advances, identify their advantages and disadvantages, and discuss their suitability as tools for gear technology.

Optical systems

Video cameras

Optical systems have been essential for observing the behaviour of fish in and around trawls for many years.

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Urquhart and Stewart (1993) listed the varying sensitivities of different cameras that have been used to record fish behaviour. Since its introduction in 1974, the silicon-diode intensified target (SIT) camera has been favoured for work in anything but the shallowest, most well lit underwater conditions. ISIT cameras (intensified SIT) provide an improvement in low light sensitivity, but are larger and far more expensive. Ten years ago, solid-state CCD (charge-coupled devices) and ICCD cameras were available, but their performance in no way matched that of the SIT. Huge improvements were predicted as the technology developed, and Figure 1 illustrates the extent of these improvements to date.

The SIT cameras manufactured today still rely on the same principle of an image intensifying tube that converts light to electrons. Second and third generation tubes have enhanced the ability to resolve detail and advances in electronics and signal processing has also improved the image quality. Sensitivity of SIT and ISIT cameras is now claimed by manufacturers to be around 2×10^{-4} and 1.5×10^{-6}, respectively. The use of ISIT cameras has been limited, mainly to military establishments and also in specialized deep-sea studies of bioluminescence (Herring *et al.*, 2000). Intensifying tubes can be coupled to CCD image sensors to produce ICCD cameras, but these also have had limited uptake in scientific underwater observation.

Digital cameras use solid-state image sensors to capture and store an image. Two kinds of sensors are available today, the CCD and the CMOS (Complementary Metal Oxide Semiconductor). The manufacturing process for CCD sensors is specialized and expensive, but is designed to minimize noise and optimize the image quality. In contrast, CMOS sensors are made using the same basic technology as 90% of semiconductor devices, making fabrication considerably cheaper and simpler as well as requiring less voltage. Image quality of CMOS sensors has recently begun to compete with and match that of the CCD sensors with 8–10 megapixel versions of both available and 100-megapixal sensors predicted (Benamati, 2001). Despite this, CCD sensors are still the choice for applications where low light sensitivity is important as they have a 100% "fill factor" (proportion of a photosite devoted to light collection) compared with CMOS sensors, where photosites are partially covered with circuitry that performs other functions.

The advantages of CCD cameras over the traditional intensified cameras are their relative robustness, smaller size, and generally lower cost. They also do not suffer from the burn-out problems of SIT and ISIT cameras caused by extreme or extended exposure to bright lights and therefore through-life costs can also be less. Until very recently, the inherent properties of the materials used to make sensors resulted in the peak sensitivity being in the infrared range of the light spectrum, which is the first to be absorbed underwater. In contrast, SIT camera sensitivity peaks in the blue–green range, coinciding with the peak spectral transmission of light in seawater. New materials are now being used for CCD sensors geared towards digital radiography X-ray imaging with significantly increased sensitivity in the blue–green range. Other technologies, such as microlenses and on-chip electron multiplication (Janesick and Putnam, 2003), are being used in a new generation of CCD cameras which claim sensitivity on a par with SIT cameras, although so is the price (Kongsberg-Simrad, pers. comm.).

Stereo camera systems

Stereophotography has been applied to the study of fish school structure, but mostly under laboratory conditions (e.g. Dill *et al.*, 1981) or in shallow brightly lit waters using hand-held units (e.g. Harvey *et al.*, 2002). Stereocinematography has also been utilized, allowing the estimation of fish swimming speed and 3-D tracking of movement (Boisclair, 1992; Hughes and Kelly, 1996). Commercially available systems have been developed which use robust, low light video cameras and purpose-written software to give non-intrusive monitoring of fish size in aquaculture (Petrell *et al.*, 1997; Sheih and Petrell, 1998). So far, this technique has not been applied to fish behaviour in relation to fish capture, although it has the potential to provide an additional spatial dimension for the relative position of individual fish inside the net.

Artificial light and laser technology

The main limitation with all optical systems remains the environment that they are required to operate in. Demersal trawling usually takes place at depths in excess of 50 m, where there is minimal ambient light. One solution is to introduce an artificial light source, but this can potentially influence the behaviour of the fish and invalidate the observations made. In an attempt to minimize this effect, flash stills photography has been used to take snap-shot images of fish ahead of fishing gear (Glass and Wardle, 1989; Walsh and Hickey, 1993). Infrared light has also been used under the assumption that fish are insensitive to this wavelength, but has a very limited range of around 1–2 m at best (e.g. Matsuoka *et al.*, 1997; Olla *et al.*, 2000).

In addition to low light levels, trawling generates suspended sediments that further restrict the visible range, through backscatter of any light. Imaging systems that use either range-gating (where backscatter is time-gated out) or synchronous scanning of laser light sources can achieve greater range, and have the ability to penetrate further into turbid waters. Laser Line Scan System (LLSS) technology developed over the past decade, uses a collimated beam of narrow wavelength light (blue–green) from a laser focused onto a spot on the seafloor via a rotating mirror assembly which scans the light spot in a "swath" perpendicular to

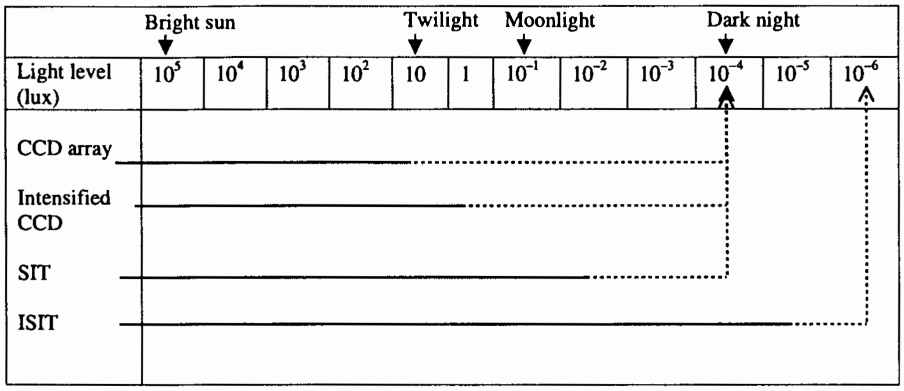

Figure 1. From Urquhart and Stewart (1993), updated to illustrate improvements in sensitivity. Black solid lines indicate sensitivity as reported by Urquhart and Stewart (1993), broken arrows show improvements in sensitivity by comparison with underwater cameras available today.

the axis of the instrument. These systems increase the range attainable by conventional optical instruments, while retaining relatively high-resolution image quality (see Figure 2). They have been successfully used in place of traditional sidescan sonar to map benthic habitats (Rhoads *et al.*, 1997; Carey *et al.*, 2003). Other applications include assessing biological communities such as king crab populations in Alaska (Tracey *et al.*, 1998) and, in a sideways orientation to assess nearshore kelp forest fish communities (Heilprin and Carey, 1994). However, for fish behaviour, the issue remains that such lasers will be visible to fish, which are likely to react either by avoiding or being attracted to the light. Preliminary tank experiments using a laser stripe system developed at Cranfield University (Tetlow and Allwood, 1995) to image groups of live haddock and whiting indicated that the fish were aware of and often attempted to avoid the swath of laser light (Tetlow *et al.*, in press). The effect of these systems when used in the context of an approaching demersal trawl remains untested.

Video analysis

To date, the vast majority of video footage obtained has been analysed qualitatively with only a few examples of quantitative results (e.g. Castro *et al.*, 1992; Thomsen, 1993; Bublitz, 1995). Recent advances in image analysis and object-tracking software may provide tools for quantitative studies, but image quality remains a limiting factor to the usefulness of off-the-shelf products. Considerable amounts of video footage have been made using towed vehicles or net-mounted cameras, and care should be taken in the interpretation of such data. O'Neill *et al.* (2003) point out the difficulties of perception that can arise when images are collected from a reference frame that also moves. This is accentuated when there is sea-state-induced vessel motion that can be transmitted down the warps to both the trawl and the towed vehicle. In their study, these authors demonstrate that to fully appreciate the fish behaviour a prior understanding of the catch and trawl dynamics is required.

Acoustics

Acoustic systems such as echosounders and multi-beam sonars are not limited by light levels or turbidity and tend to have a much greater operational range and in the case of sonars also a much wider field of view. The two main acoustic tools in current use are the vertical echosounder and the multi-beam sonar. These will be considered separately.

Vertical echosounders

Downward-looking echosounders mounted on vessels or towed bodies can be used to observe fish behaviour underway (Misund, 1997). Much of this work concentrates on pelagic fish, but there are applications in demersal stock estimation where acoustic and bottom-trawl observations are available. A good example is the case of the Barents Sea cod (Michalsen *et al.*, 1996; Jakobsen *et al.*, 1997). Hjellvik *et al.* (2002) demonstrated the different behaviours of cod under different stock scenarios and how a combination of acoustic and trawl data could be used to measure error. A similar approach was used by Cachera *et al.* (1999) for catchability in bottom-trawl surveys in the North Sea, and is being developed under a new European project (CATEFA).

Mounting the echosounder on a platform remote from the vessel has a number of advantages. In a towed body, the distance from the sounder to the fish is reduced for precise observations (Øvredal and Huse, 1999). Echosounders mounted on moored (Ona and Godø, 1990) or drifting buoys (Godø *et al.*, 1999; Wilson and Demer, 2001; Handegard *et al.*, 2003) have been used to examine changes in behaviour of fish as a vessel passes using target-tracking

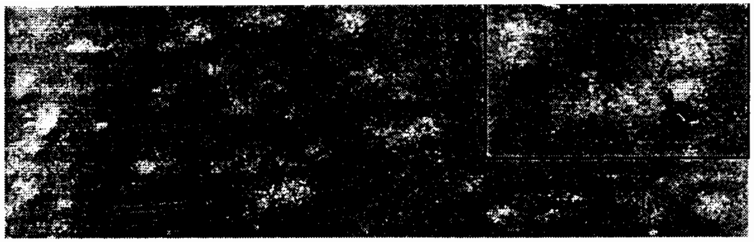

Figure 2. Digital image obtained from the Northrup Grumman SM2000 Laser Line Scan System mounted on a McCartney Underwater Technology FOCUS tow body operated by SAIC (Science Applications International Corporation). The image shows dogfish in shallow mounds at 78-m depth from an altitude of 8.5 m. (Image reprinted from Carey *et al.*, 2003.)

methods. In a development of this approach, the sounder can also be mounted on an Autonomous Underwater Vehicle (AUV), which can move independently ahead of the vessel (Fernandes *et al.*, 2000). This type of system could, for example, be used for monitoring change in the behaviour of demersal fish between the vessel and a towed [illegible] looking upwards to compare distributions under the vessel and over the net (Michalsen *et al.*, 1999).

Sonars

Sonar systems, conventionally any non-vertical sounder deployment, as well as the more complex scanning and multi-beam systems, have a long history in the observation of fish behaviour in relation to fishing gear. Harden Jones *et al.* (1977) used a searchlight sonar to follow transponder-[illegible] (1990) used a headline mounted scanning sonar (330 kHz)

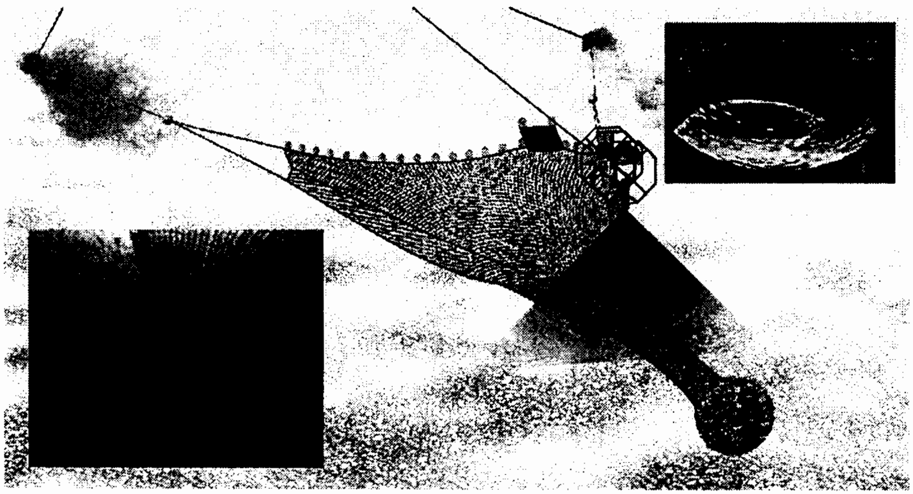

Figure 3. Illustration showing how and ROV-mounted multibeam sonar and net-mounted cameras can be combined to observe fish entering a trawl. Upper right-hand image shows the display from a Reson multi-beam sonar. Lower left-hand image shows a still image captured from the net-mounted video camera.

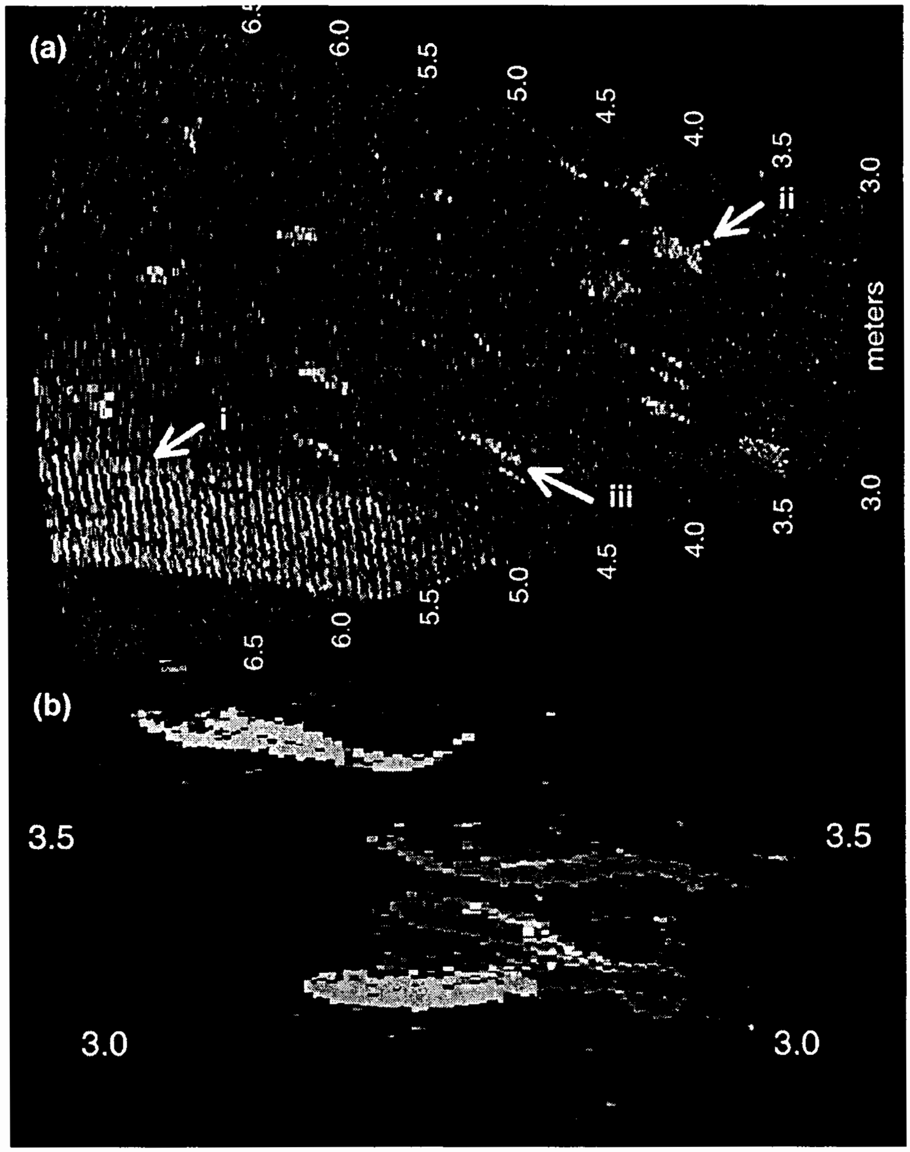

Figure 4. (a) Image taken from output from a DIDSON unit mounted on a pelagic trawl. The lower mesh panel of the net is visible at 5.5 m. (i) Chum salmon (*Salmo keta*) are identified by their crescent-shaped tail (ii) and remaining targets are walleye pollack (*Theragra chalcogramma*), e.g. (iii). Image, courtesy of Craig Rose, NOAA. (b) Image from DIDSON output of salmon moving upstream. Yellow indicates the fish has been counted and sized. Image, courtesy of Applied Physics Laboratory, University of Washington.

to identify the entrance position of individual fish in a survey trawl. Multi-beam sonars have been applied very successfully to study the behaviour of schooling pelagic fish (e.g. Fréon *et al.*, 1996; Mackinson *et al.*, 1998; Misund *et al.*, 1998; Gerlotto *et al.*, 1999), and should have significant applications in bottom-trawl studies. Recent experiments have combined multi-beam sonars mounted on a towed vehicle and net-mounted cameras operating over a shorter range to make detailed observations of fish entering and escaping a bottom trawl (Figure 3) (Jones *et al.*, 2001). The sonars mentioned above generally operate between 200 kHz and 500 kHz and can be used over a range of tens to hundreds of metres, depending on whether the target is a single fish or a school. However, even within a 10-m range fish are distinguished only as targets of certain intensity. At higher frequencies, increased resolution is attained. The DIDSON (Dual Frequency Identification Sonar) operates at 1 MHz or 1.8 MHz and was developed as an "acoustic camera" for use in turbid waters (Belcher and Lynn 2000; Moursund *et al.*, 2003). With this sonar, fish are clearly recognizable and different species can be identified in some situations by their distinctive shape and swimming movement (Figure 4; C. Rose, pers. comm.). These improvements come at a price of reduced operating range (30 m at

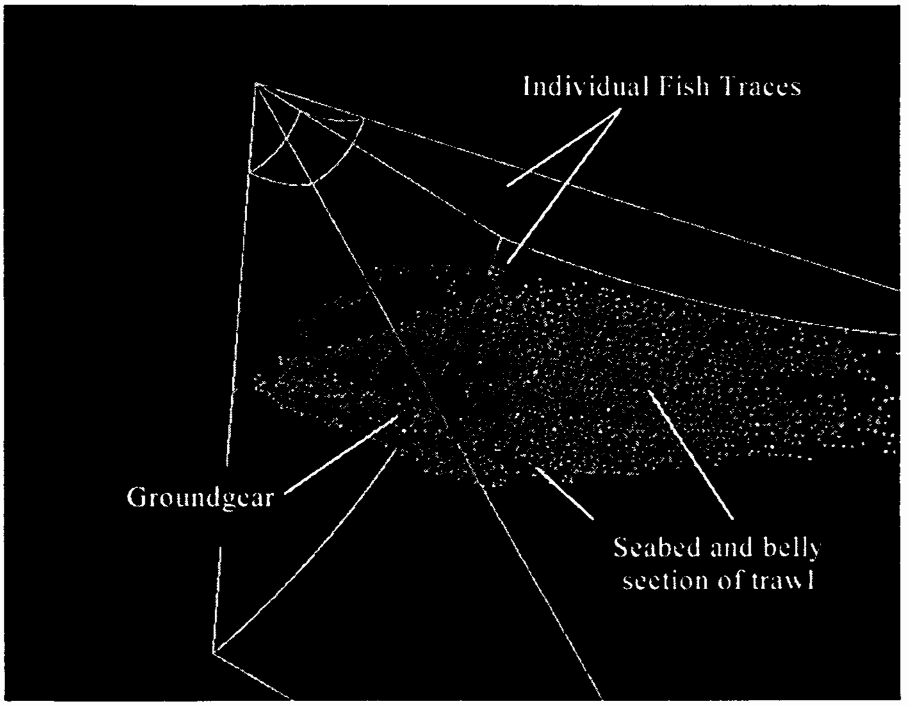

Figure 5. Processed output generated from EchoScope sonar mounted on the headline of a demersal trawl showing traces from two individual fish in a 3-D volume (approximate distance from groundgear to rearmost part of trawl belly ~6 m).

1.0 MHz and 12 m at 1.8 MHz), but nevertheless are adequate for observations within a trawl.

Sidescan sonar, usually used for mapping topography or long-range detection of fish schools, has recently been adapted for the study of fish in relation to fishing gears (Doolittle and Patterson, 2003). A 600 kHz sidescan (Marine Sonic Technology Ltd) is mounted in a Fetch class AUV (Autonomous Underwater Vehicle) or a conventional towed vehicle. The acoustic image data obtained were processed using a Radial Basis Function Artificial Neural Network to allow semi-automated fish identification to species. To date, trials have shown that the system can discriminate sharks (*Carcharias taurus*) and jacks (*Caranx hippo*) from other fish species. This development begins to address the key weakness of acoustic techniques, the identification of the fish targets seen in the echogram. The problems of distinguishing between similar fish, e.g. gadoids, have yet to be explored.

All these tools are effectively 2-D systems, although post-processing can create a quasi-3-D view by building up images over time (Gerlotto *et al.*, 1999). A genuine 3-D view is obtained with the EchoScope 1600 (OmniTech AS, Norway). Developed as a visual tool for ROV operations and pipeline surveying, a single pulse is generated simultaneously from 4064 beams. Time-gated echoes from the pulse are collected by an array of 1600 hydrophones and then "stacked" to produce a fully geo-referenced 3-D image which can be viewed in a virtual environment, from any angle, and all in real time. The EchoScope has been successfully mounted on a demersal trawl and the x, y, and z coordinates of individual fish moving through the beam have been obtained as shown in Figure 5 (N. Graham, pers. comm.). The volume of data generated necessitates the use of a fibre optic cable to the surface. In common with many trawl to surface systems, such as netsonde, there is concern relating to the influence on trawl geometry and fish behaviour due to the presence of the cable (Michalsen *et al.*, 1999; Handegard *et al.*, 2003), which may be difficult to overcome.

Acoustic data processing

Many of the new generation acoustic devices have been developed for industry applications and are designed to remove midwater returns. In order to be of use for behavioural observations, the ability to collect and process raw data is essential. These issues will need collaboration between biologists and industry to achieve them. In processing and interpreting data, issues such as variability of target strength with aspect of the fish, problems with scattering and stratification of the water column, and high reflectance of other materials such as groundgear, netting, and floats will need to be addressed. The volume of raw data produced, particularly from multi-beam sonars, is considerable (e.g. 45 MB min^{-1}), and processing power is highly important. Recent advances in computer hardware and software have allowed faster, more efficient techniques for data display and analysis, e.g. Echoview and Matlab packages, should be made use of.

Summary

Substantial improvements have been achieved in both optical and acoustic techniques in terms of both hardware and post-processing software. Unfortunately, the environment in which we intend to use such tools has changed very little and remains hostile to all equipment. The use of cameras without artificial illumination will always be restricted in turbid and very low light conditions. Acoustic systems can operate independently of these limitations and therefore offer the ability to observe fish behaviour at night and at greater depths. Depending on the frequency used, observations can also be made at much greater ranges (from tens to hundreds of metres), although with an accompanying loss of resolution and ability to distinguish individuals or species. The best way forward, it seems, is to use a combination of these approaches, and, as such, the challenge will be integration and processing of data. Despite the complexities of the equipment and the difficulties caused by the environment, a considerable amount of innovative research is being conducted with these new techniques. Significant inroads into quantifying behavioural reactions in low light levels, at greater depths, and at greater ranges are being made. In turn, these data are being utilized for the development of more species-selective gears and to provide improved efficiency estimates for survey trawls.

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